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(SOURCE): International Society for Terrain-Vehicle Systems

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A COMPARISON BETWEEN A CONVENTIONAL METHOD AND AN IMPROVED METHOD FOR PREDICTING TRACKED VEHICLE PERFORMANCE

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INTRODUCTION

One of the most widely used conventional methods for predicting tracked vehicle performance is based on the assumption that the track in contact with the terrain is equivalent to a rigid footing. Furthermore, a uniform normal pressure distribution over the entire contact area is assumed if the centre of gravity of the vehicle is located at the midpoint of the contact length. On the other hand, if the centre of gravity is located in front or behind the midpoint of the contact length or if load transfer due to drawbar pull takes place a sinkage distribution of trapezoidal shape will then be assumed. Based on these assumptions and the measured pressure sinkage and shear stress displacement relationships of the terrain, the tractive performance of tracked vehicles is predicted.

Experimental evidence has shown that while the conventional method may find applications in the prediction of the performance of crawlers with low ratios of roadwheel spacing to track pitch, commonly used in agriculture and the construction industry, it gives unrealistic prediction of the performance of tracked vehicles with high ratios of roadwheel spacing to track pitch designed for high speed operations. In the latter case, the normal pressure is usually concentrated under the roadwheels and is far from uniform. Consequently, the track in contact with the deformable terrain deflects and has the form of a curve. Furthermore, an element of the terrain under the track is subject to repetitive normal and shear loadings of the consecutive roadwheels. To take these factors into account, an improved method for predicting the performance of tracked vehicles with relatively short track pitch has been developed. The objective is to provide the designer, the procurement manager and the test engineer with a quantitative means whereby the effects of vehicle design parameters and terrain conditions on performance can be assessed more realistically than using the conventional method.

This paper describes a comparison of the normal pressure distribution, sinkage and drawbar pull slip relationship of a tracked vehicle as predicted using the conventional and the improved methods.

THE CONVENTIONAL METHOD

One of the widely used conventional methods assumes that the track behaves like a rigid footing. With the centre of gravity of the vehicle at the midpoint of the contact length, the normal pressure distribution is assumed to be uniformly distributed as shown in Fig. 1. On the other hand, if the centre of gravity is located in front or behind the midpoint of the contact length, a sinkage distribution of trapezoidal shape is assumed.

If the pressure-sinkage relationship of the terrain is known, such as that shown in Fig. 1, then the sinkage z of the track can be predicted by equating the reaction due to normal pressure p with the vehicle weight (1) (2). The functional relationship between sinkage z and pressure p for a given terrain can generally be expressed by

$$z = f(p) \qquad (1)$$

It should be mentioned that the pressure-sinkage relationship may vary with terrain type and conditions. Various methods have been proposed for characterizing the pressure-sinkage relations of different kinds of terrain as described in references (1), (2), (3), (4) and (5).

Based on the predicted track sinkage z_0, the motion resistance R_c due to terrain compaction can be predicted as follows:

$$R_c = b \int_0^{z_0} p\,dz \qquad (2)$$

where b is the width of the track.

In addition to resistance due to compaction, the track may encounter resistance due to buildozing effects (1). This should be taken into account in determining the total motion resistance.

If the shear stress - displacement relationship of the terrain under an appropriate normal pressure p is known, such as that shown in Fig.1, the tractive effort of a track F can be predicted as follows:

$$F = b \int_0^{\ell} s\,dx \qquad (3)$$

where ℓ is the length of the track and s is the shear stress under the track which varies along the contact length (1), (2).

If the shear stress - displacement relationship can be described by a simple exponential function (1)(2), the tractive effort F at a given slip i can be expressed by (1)(2)

$$F = (Ac + W\tan\phi)\left[1 - \frac{K}{i\ell}\left(1 - e^{-i\ell/K}\right)\right] \qquad (4)$$

where A and W are the contact area and normal load of the track, respectively, c and ϕ are cohesion and angle of internal shearing resistance of the terrain, respectively; K is the shear deformation modulus of the terrain.

It should be pointed out that the shear stress-displacement relationship may vary with terrain type and conditions. Various methods have been proposed for characterizing the shear stress - displacement relations of different kinds of terrain as discussed in references (1)(2) and (6).

Based on the predicted motion resistance and tractive effort, the drawbar pull-slip relationship of a tracked vehicle can then be estimated. The drawbar pull-slip relationship forms a basis for the comparison and evaluation of the tractive performance of off-road vehicles.

THE IMPROVED METHOD

When a tracked vehicle with relatively short track pitch travels over a deformable terrain, the normal load is usually concentrated under the roadwheels. However, the track segments between the roadwheels also take up load(7). As a result, they deflect and have the form of a curve. Furthermore, an element of the terrain under the track is subject to the repetitive loading of consecutive roadwheels (8). To predict the normal pressure distribution on the track-terrain interface, the pressure-sinkage relationship and the response to repetitive loading of the terrain have to be measured. Fig. 2 shows the response of a muskeg to repetitive loading (4). It shows that the stiffness of the muskeg during unloading and reloading is much higher than that in its virgin state and that it exhibits a certain amount of hysteresis.

When the terrain characteristics are known, the prediction of the normal pressure distribution is reduced to the determination of the shape of the deflected track in contact with the terrain. A detailed analysis of the mechanics of track-terrain interaction has been made. The track system with the major interacting forces are shown in Fig. 3. In the analysis, it is assumed that the track is equivalent to a flexible and inextensible belt and that the roadwheels are rigidly connected to the vehicle body. A set of equations for the equilibrium of the forces and moments acting on the track system and the conservation of overall track length have been derived. They establish the relationship between the shape of the deflected track in contact with the terrain and vehicle design parameters and terrain characteristics. The solution to this set of equations defines the sinkages of the roadwheels and the shape of the track segments between roadwheels. From these, the normal pressure distribution under a moving tracked vehicle can be predicted. The details of the analysis are described in reference (9).

To predict the shear stress distribution, the shear stress-displacement relationship of the terrain and the characteristics of the track-terrain shearing have to be determined. It should be mentioned that an element of the terrain under the track is also subject to shearing action of a repetitive nature. This is because the normal load applied to an element of the terrain under the track varies as the consecutive roadwheels roll over it. As a result, for a terrain exhibiting frictional behaviour, it undergoes the loading-unloading-reloading cycle in shear, similar to that for normal load. To predict the shear stress distribution on the track-terrain interface, the response to repetitive shear loading of the terrain must be known. Fig. 4 shows the response of a frictional medium (a dry sand) to repetitive shear loading. It indicates that for a frictional terrain, the shear stress-displacement relationship during reloading is similar to that with the terrain in its virgin state. This means that when re-shearing takes place after the previous loading-unloading cycle, the shear stress does not instantaneously reach its maximum value for a given normal stress. Rather a certain amount of shear displacement must take place before the maximum shear stress can be developed, similar to that when the frictional medium is being sheared in its virgin state. This phenomenon has been taken into account in the analysis. Together with the knowledge of the shear displacement developed under the track, which can be determined by a kinematic analysis of the track based on the concept of slip velocity (1)(2), the shear stress distribution under the track can then be predicted. Fig. 5 illustrates how the development of the shear stress under the track may be modified if the response of a frictional terrain to repetitive shear loading is taken into account for an idealized case. It should be pointed out that when the

repetitive shearing characteristics of the terrain are taken into consideration, the predicted total tractive effort of the vehicle at a given slip may be considerably lower than that when they are not taken into account, as can be seen from Fig. 5. The details of the analysis are given in reference (9).

When the normal pressure and shear stress distributions have been determined, the motion resistance, tractive effort and drawbar pull as functions of slip can be predicted. The prediction procedures have been programmed on a Hewlett-Packard 9845T microcomputer. The required inputs include both the vehicle and terrain parameters. The computer outputs include normal pressure and shear stress distributions, sinkage, motion resistance, tractive effort and drawbar pull at a given slip (8) (9).

A COMPARISON BETWEEN THE CONVENTIONAL METHOD AND THE IMPROVED METHOD

The normal pressure distribution, the sinkage of the track and the drawbar pull-slip relationship of a tracked vehicle, with basic parameters shown in Table 1, operating over a variety of terrains were predicted using the conventional and the improved methods. The parameters used to characterize the pressure-sinkage relationships and the response to repetive normal load for a sandy terrain and two muskegs are given in Tables 2 and 3, respectively. The shear strength parameters of the terrains used in the predictions are given in Table 4. For further information concerning the methods used to characterize terrain behaviour, please refer to references (3), (4), (5), (6) and (9).

A comparison between the predicted normal pressure distributions using the conventional and the improved methods and field measurements over a sandy terrain and a muskeg are shown in Figs. 6 and 7, respectively. It can be seen from Fig. 6 that over the sandy terrain the maximum pressure predicted by the improved method is quite close to the measured one, whereas that estimated using the conventional method is 43.7 kPa, only about 10% of the maximum measured pressure. Over the muskeg, the normal pressure estimated using the conventional method is again 43.7kPa, about 40% of the maximum measured. However, the maximum normal pressure predicted using the improved method is again quite close to the maximum measured as shown in Fig. 7. The reason is that in the improved method the response of the terrain to repetitive normal load has been taken into account. As mentioned previously, after the terrain has been compacted by the first roadwheel, it becomes much "stiffer" than in its virgin state. This promotes the concentration of normal pressure under the roadwheels. The behaviour of the terrain during the unloading-reloading cycle shown in Fig. 2 also explains why it is possible that the normal pressure at a point on the track segment between two adjacent roadwheels can be as low as zero, while the sinkage at that point as measured from the original terrain surface is not zero.

Figs. 8 and 9 show a comparison between the predicted sinkages of the vehicle using the conventional and the improved methods and the measured sinkages over the two types of terrain. It can be seen that in general the conventional method underestimates the sinkage. This is because the normal pressure estimated using the conventional method is considerably lower than the actual maximum pressure. On the other hand, it can be seen that fair to good agreement exists between the measured sinkages and those predicted using the improved method.

A comparison between the measured drawbar pull-slip curves and those predicted using the conventional and the improved methods over the sandy terrain and the muskeg are shown in Figs. 10 and 11, respectively. It can be seen that the conventional method overestimates the drawbar pull of the vehicle over the full range of vehicle slip, particularly at low track slips. It is also shown that there is a close agreement between the measured drawbar pull and that predicted using the improved method. This is because the improved method gives a more realistic prediction of vehicle sinkage and hence motion resistance. Furthermore, the response of the terrain to repetitive shear loading, as described in the previous Section, has been taken into account in the improved method.

It is interesting to note that the significant difference in the drawbar performance between a crawler used in construction industry and a high speed tracked vehicle of similar size and weight reported in reference (10) is parallel to that between the two drawbar pull-slip curves shown in Figs. 10 and 11.

CLOSING REMARKS

It is shown that the improved method outlined in this paper gives a more realistic prediction of the performance of tracked vehicles with high ratios of roadwheel spacing to track pitch than the conventional method. The improvement achieved is due primarily to the inclusion of the response of terrain to repetitive normal and shear loadings and to the detailed analysis of the mechanics of track-terrain interaction.

It is believed that the improved method outlined in the paper provides a quantitative means for evaluating the effects of vehicle design parameters and terrain conditions on tracked vehicle performance and for comparing the performance of different tracked vehicle designs.

ACKNOWLEDGEMENTS

The improved method outlined in this paper was developed under contract arrangements with the Department of National Defence, Canada, through the Department of Supply and Services. The project was administered by the Vehicle Mobility Section, Defence Research Establishment Suffield, Alberta, Canada.

REFERENCES

1. M.G. Bekker, Introduction to Terrain-Vehicle Systems, The University of Michigan Press, 1969.

2. J.Y. Wong, Theory of Ground Vehicles, John Wiley, New York, 1978. Russian edition, Machinostroenie Publishers of Moscow, U.S.S.R., 1982.

3. J.Y. Wong, "Data processing methodology in the characterization of the mechanical properties of terrain", Journal of Terramechanics, Vol. 17, No. 1, pp. 13-41, 1980.

4. J.Y. Wong, J.R. Radforth, and J. Preston-Thomas, "Some further studies on the mechanical properties of muskeg in relation to vehicle mobility", Journal of Terramechanics, Vol. 19, No. 2, 1982.

5. J.Y. Wong and J. Preston-Thomas, "On the characterization of the pressure-sinkage relationship of snow covers containing an ice layer", Journal of Terramechanics, Vol. 20, No. 1, 1983.

6. J.Y. Wong and J. Preston-Thomas, "On the characterization of the shear stress-displacement relationship of terrain", Journal of Terramechanics, Vol. 19, No. 4, 1982.

7. M.G. Bekker, Theory of Land Locomotion, The University of Michigan Press, 1956.

8. J.Y. Wong, "An improved method for predicting tracked vehicle performance", Proceedings of the Second European Conference of the International Society for Terrain-Vehicle Systems, Ferrara, Italy, October 3-5, 1983.

9. J.Y. Wong, M. Garber, and J. Preston-Thomas, "Theoretical prediction and experimental substantiation of the ground pressure distribution and tractive performance of tracked vehicles", to be published.

10. D.R. Freitag, Discussion on a paper entitled "Measurement of soil shear strength and deformation moduli and a comparison of the actual and theoretical performance of a family of rigid tracks", by B.M.D. Wills, Journal of Terramechanics, Vol. 2, No. 1, pp. 93-95, 1965.

Table 1

Vehicle Parameters

Vehicle Weight, kN	88.72
Number of roadwheels (for one track)	5
Radius of roadwheels, m	0.31
Distance between roadwheels, m	0.67
Distance between the centres of the sprocket and the tensioning wheel, m	4.03
Width of track, m	0.38
Track pitch, m	0.15
Initial track tension, kN	8.54
Weight of the track per unit length, kN/m	1.27
Height of track grousers, cm	3.7
Number of supporting rollers	0
Angle of approach of the track, degrees	23.8
Angle of departure of the track, degrees	16.4
Location of centre of gravity in the longitudinal direction (in front of the mid-point of the track contact length), m	0.13
Height of the centre of gravity, m	0.99
Location of drawbar in the longitudinal direction (distance from the mid-point of the track contact length), m	2.29
Height of drawbar, m	0.75

Table 2

Values of the Pressure-Sinkage and Repetitive Loading

Parameters for a Sandy Terrain (LETE Sand)

k_c	k_ϕ	n	k_o	A_u
kN/m^{n+1}	kN/m^{n+2}		kN/m^3	kN/m^4
102	5301	0.793	0	503,000

Note: k_o and A_u are parameters used to characterize the response to repetitive normal loading.

Table 3

Values of the Pressure-Sinkage and Repetitive Loading

Parameters for Two Types of Muskeg

Muskeg Type	Petawawa Muskeg A	Petawawa Muskeg B
k_m, kN/m^3	290	762
M_m, kN/m^3	51	97
k_o, kN/m^3	123	147
A_u kN/m^4	23540	29700

Note: k_o and A_u are parameters used to characterize the response to normal loading.

Table 4

Shear Strength Parameters of Various Types of Terrain

Terrain Type	Type of Shearing	Cohesion (Adhesion) kPa	Angle of Shearing Resistance degrees	K cm
LETE Sand	Internal	1.27	31.1	1.1
LETE Sand	Rubber-Sand	0.66	27.5	1
Petawawa Muskeg A	Peat (Internal)	2.83	39.4	3.1
Petawawa Muskeg B	Peat (internal)	2.55	39.2	3.1

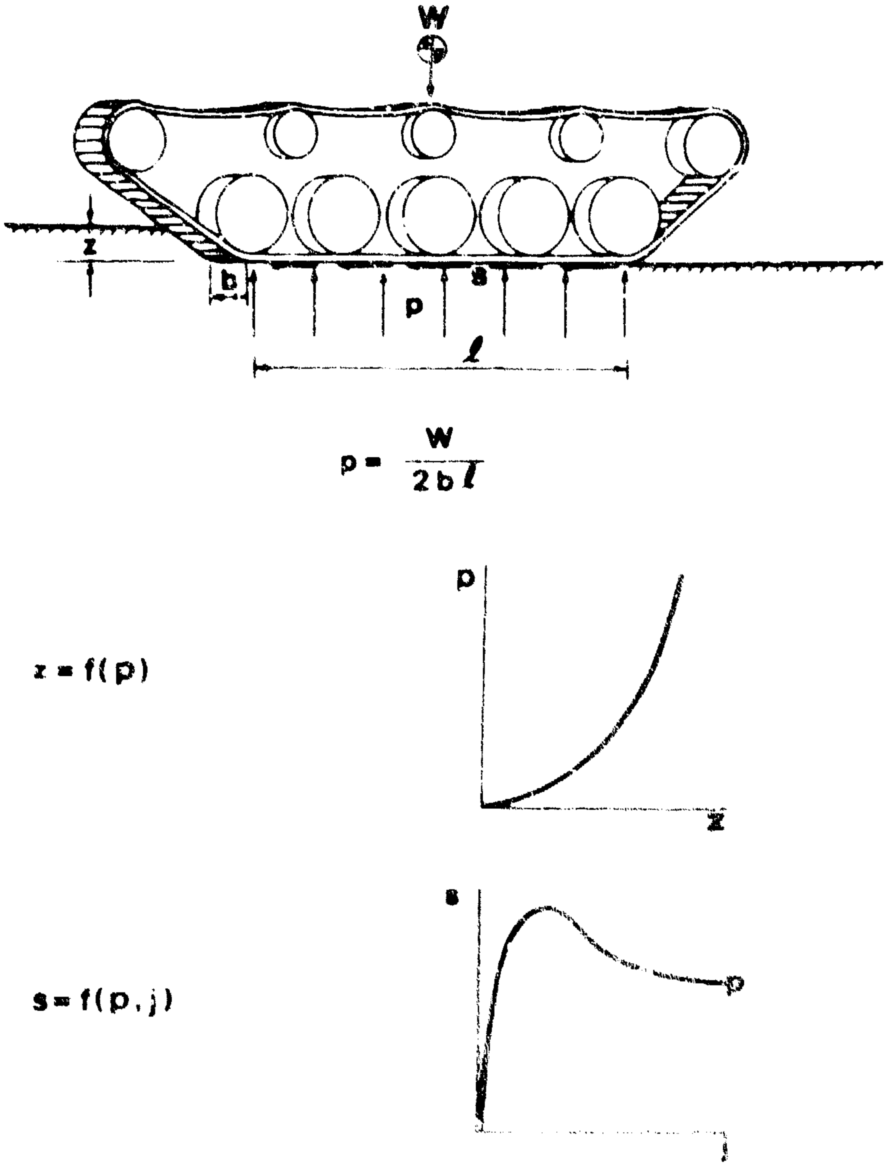

Fig. 1 The conventional method for predicting tracked vehicle performance.

BEVAMETER DATA ACQUISITION SYSTEM
Transport Technology Research Laboratory
Carleton University, Ottawa, Canada

Pressure-Sinkage Experiments: Date:22/07/81

Terrain: Petawawa Muskeg 04

Experiment number - 1 Data-Base Id.: P6-9-2

The footing radius (cm): 7.5
The X-increment (cm): 1.0

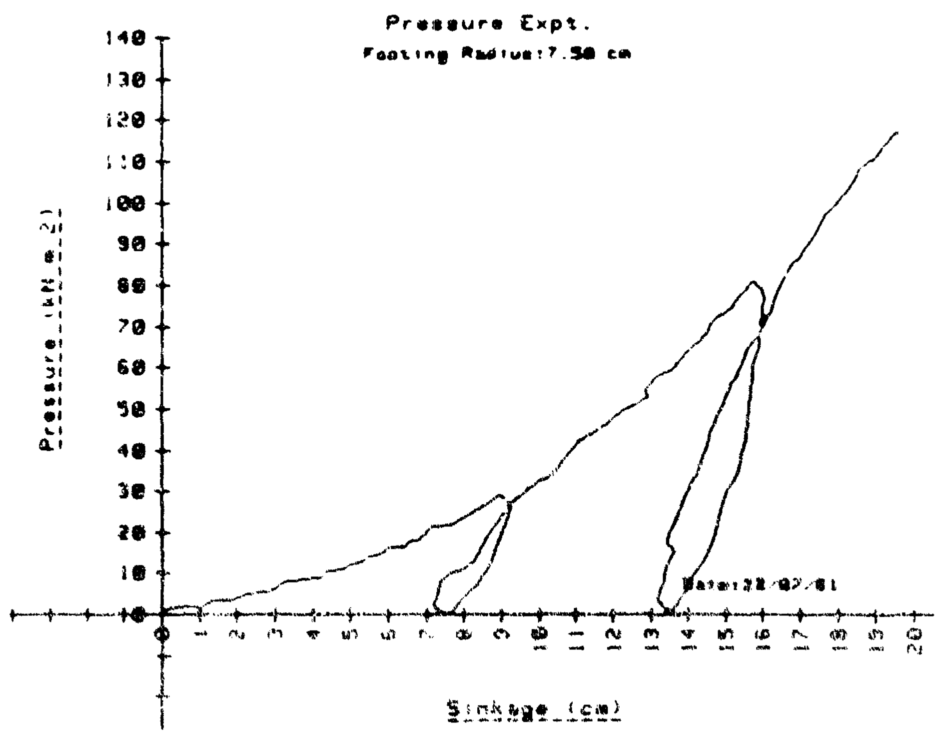

Fig. 2. Response of a muskeg to repetitive normal load.

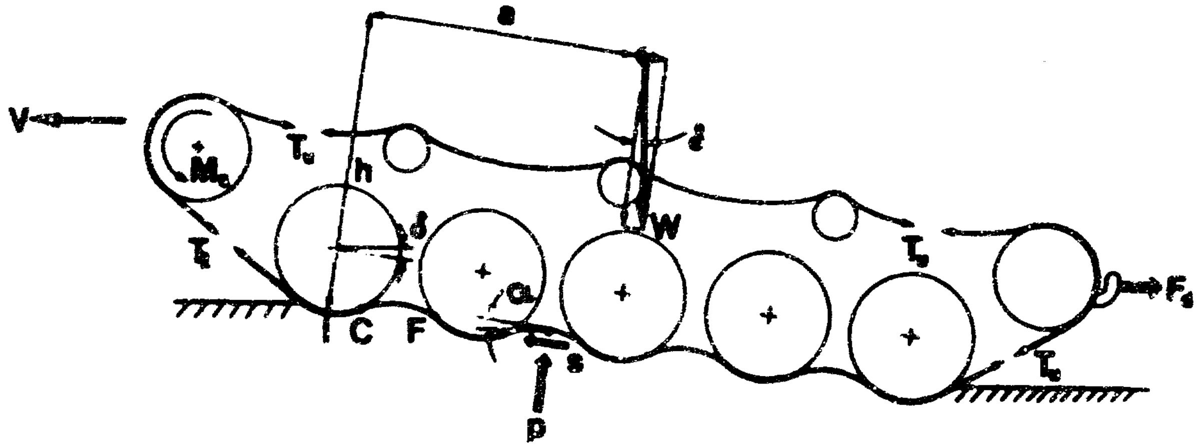

Fig. 3. Interation between a flexible track and terrain.

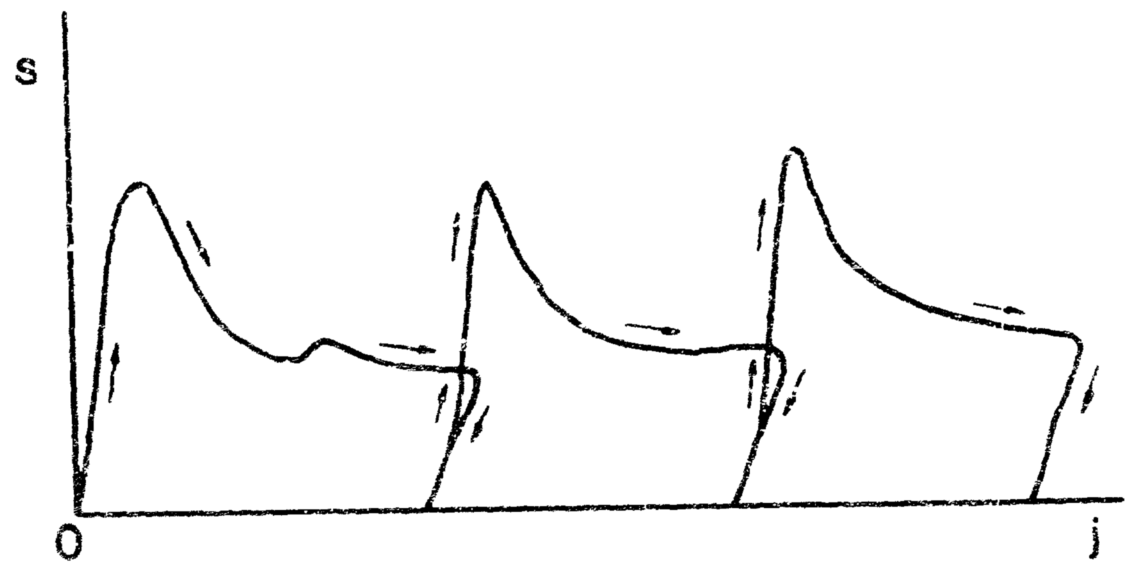

Fig. 4. Response of a frictional terrain to repetitive shear load.

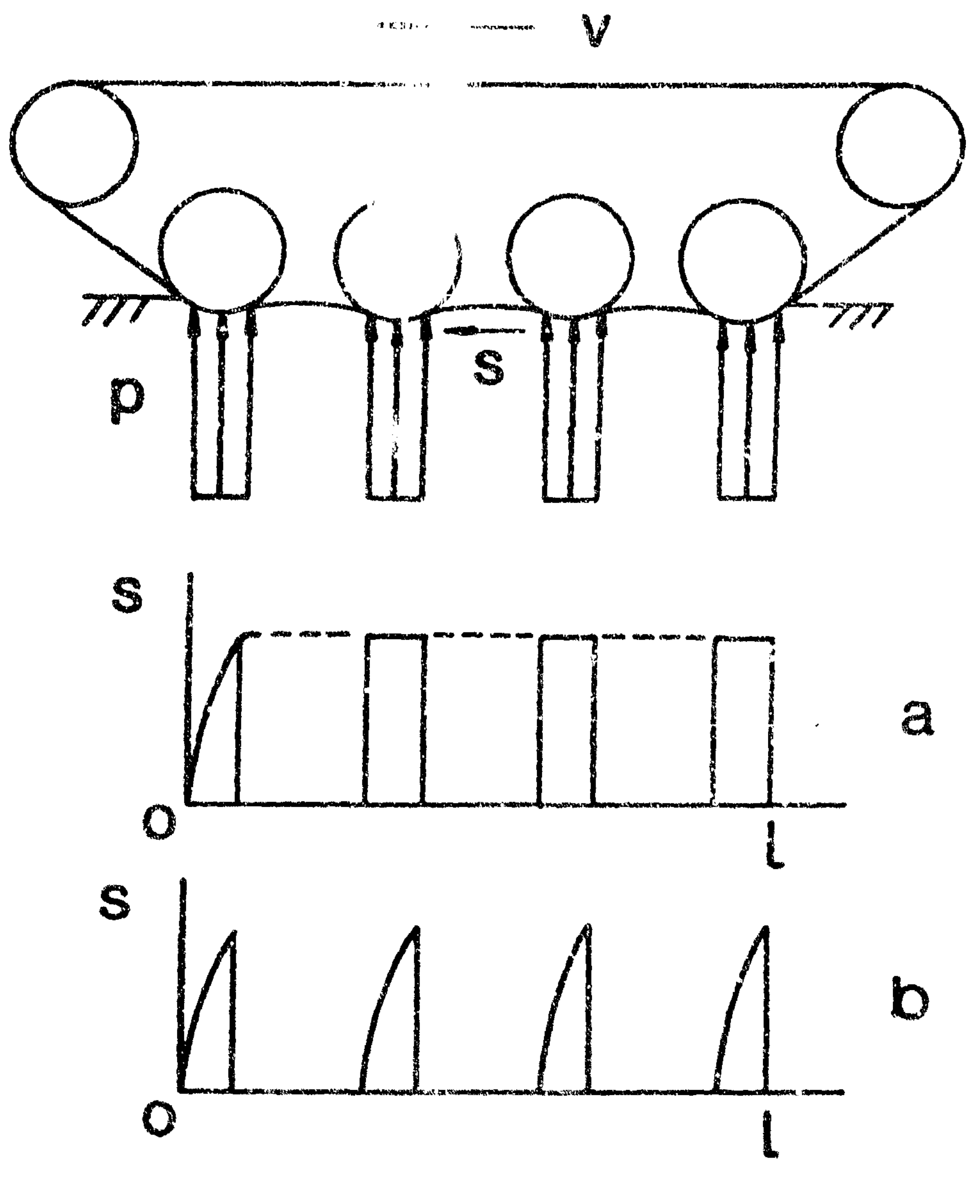

Fig. 5. Development of shear stress under a track over frictional terrain predicted by a) the conventional method and b) the improved method.

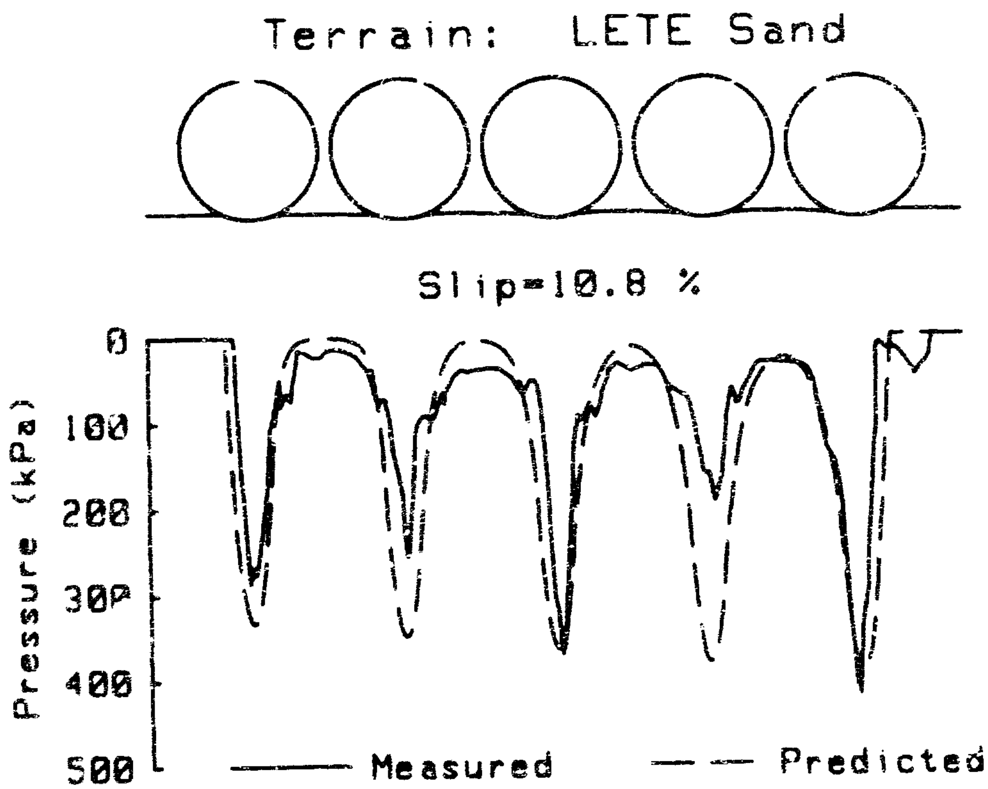

Fig. 6. Comparison of the pressure distribution predicted by the improved method with the measured one over a sandy terrain.

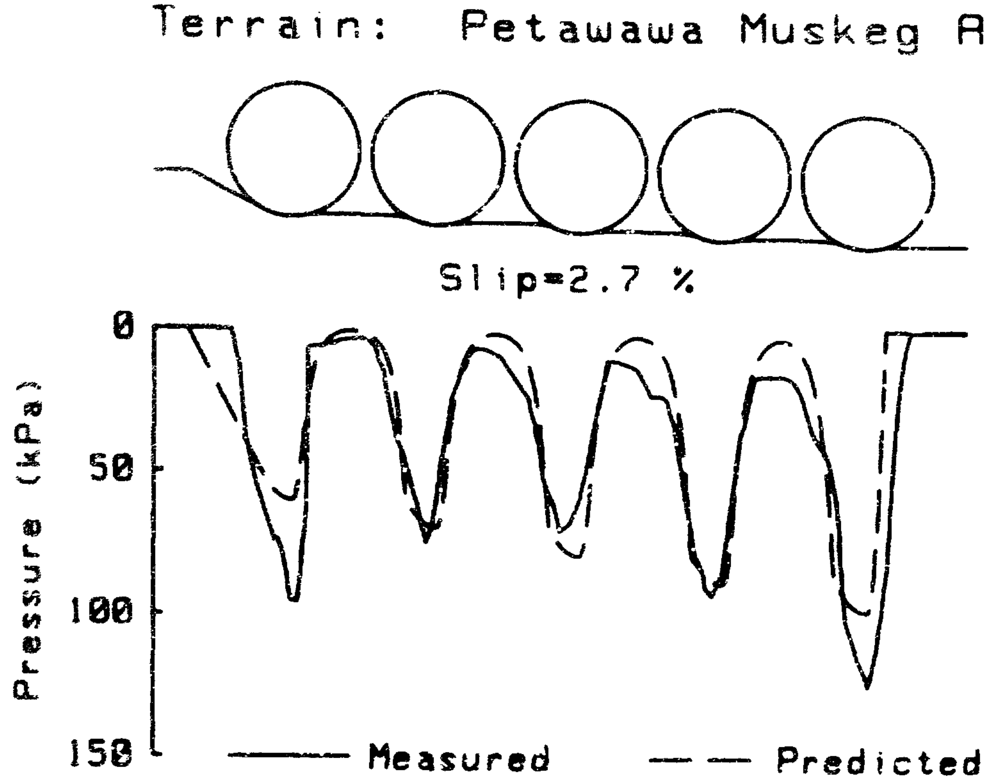

Fig. 7. Comparison of the pressure distribution predicted by the improved method with the measured one over a muskeg.

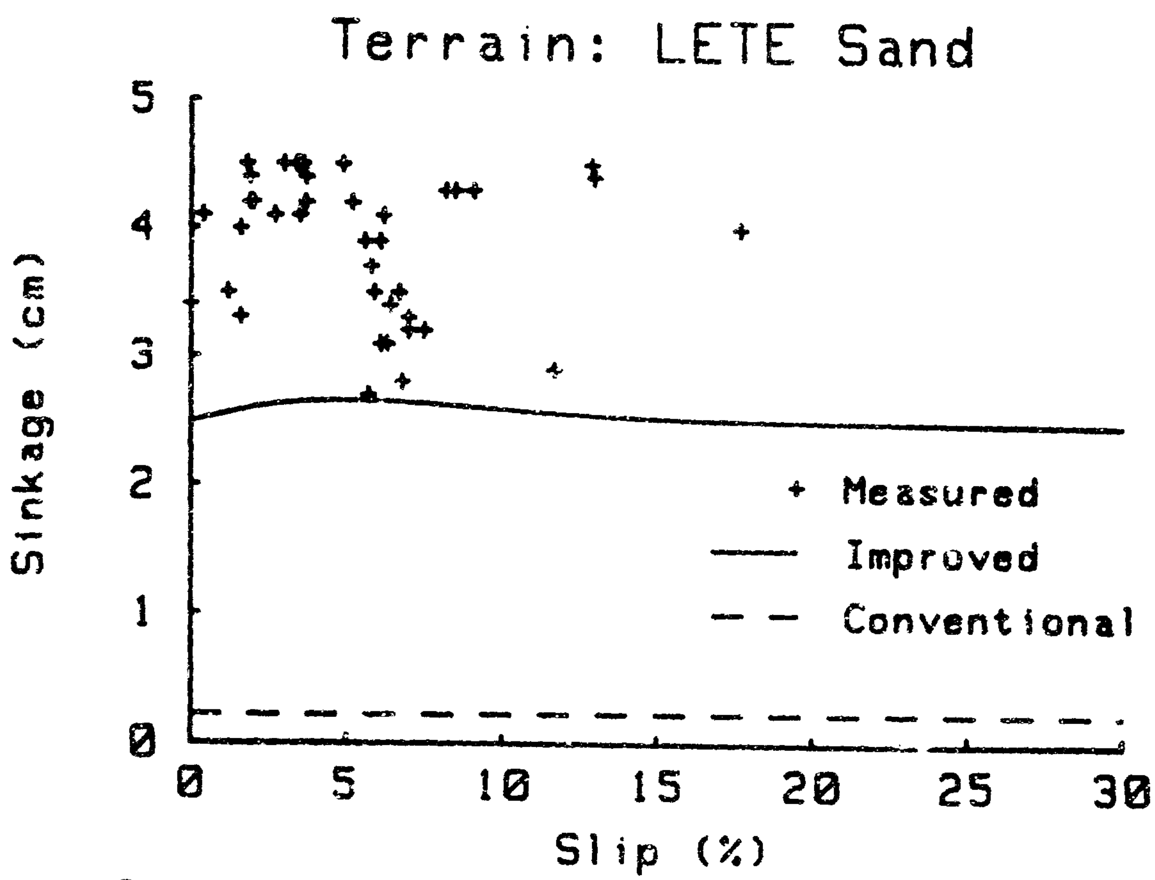

Fig. 8. Comparison of the sinkages predicted by the conventional and the improved methods with the measured ones over a sandy terrain.

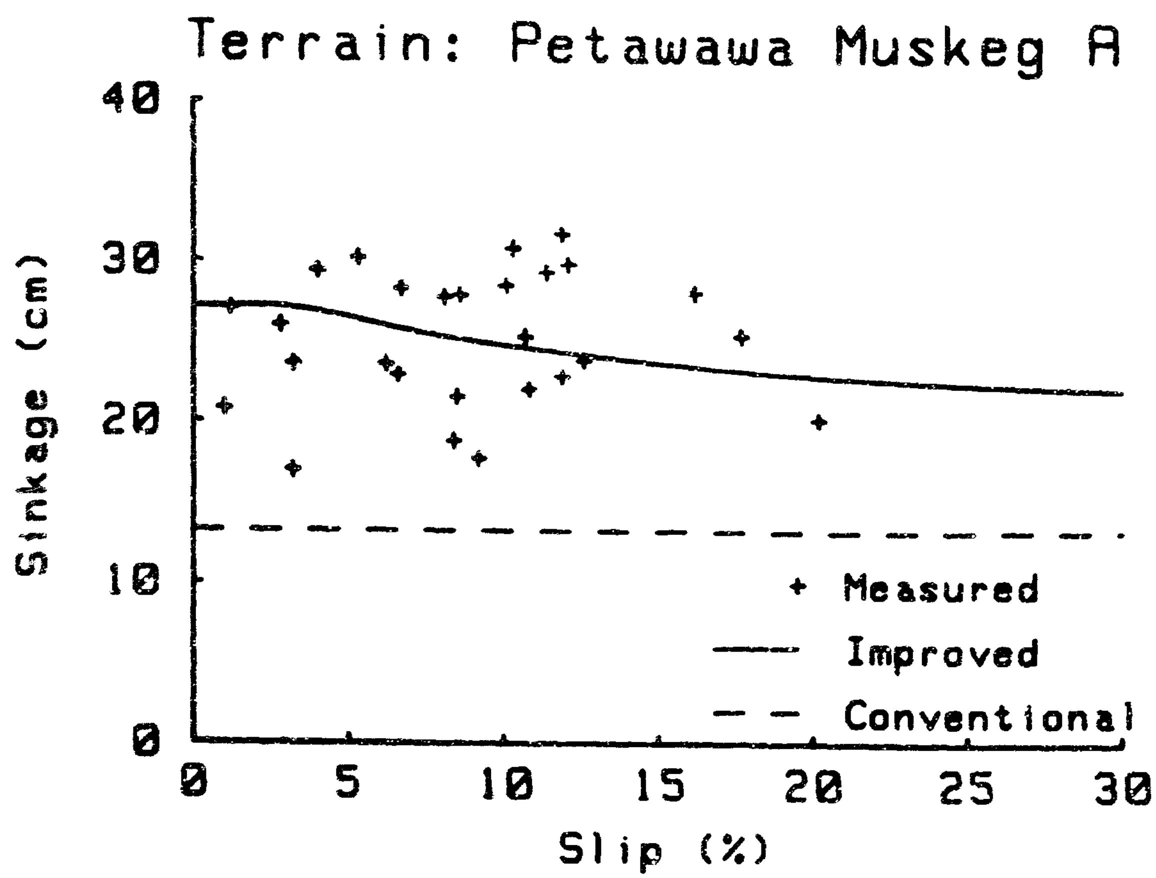

Fig. 9. Comparison of the sinkages predicted by the conventional and the improved methods with the measured ones over a muskeg.

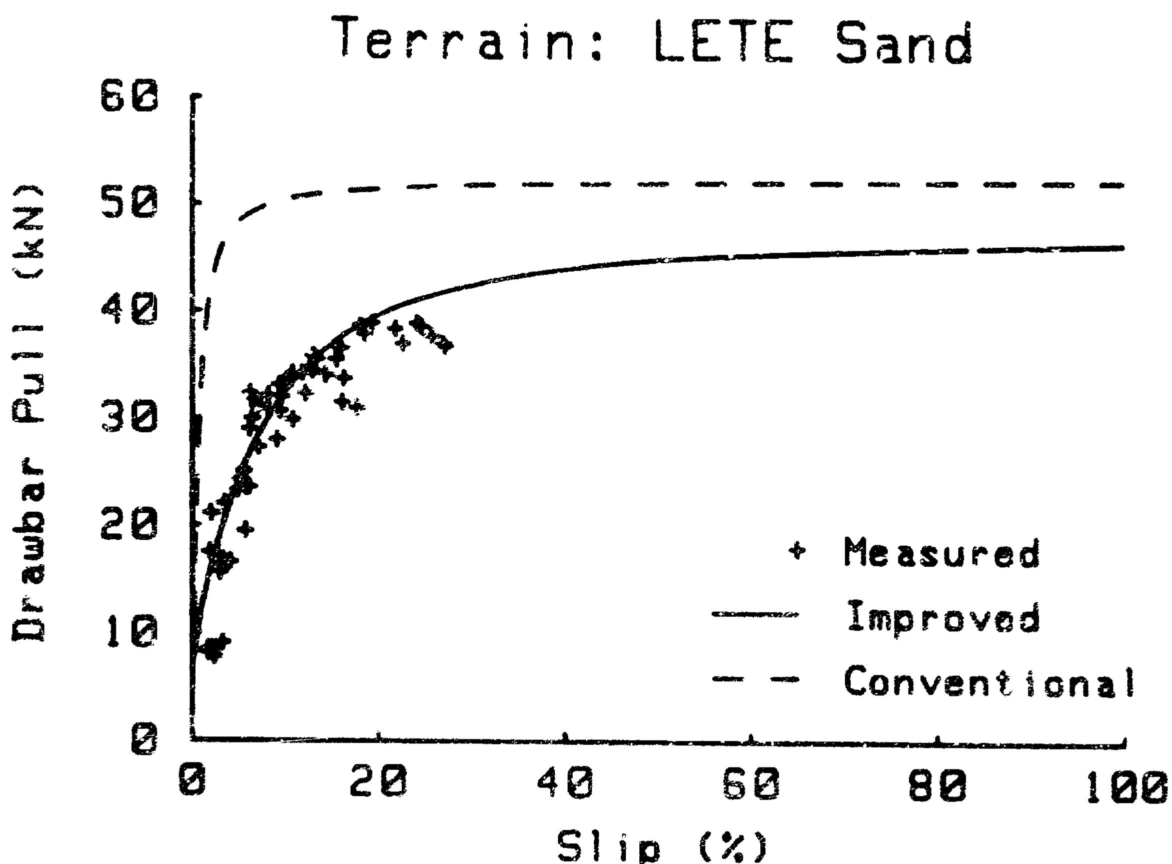

Fig. 10. Comparison of the drawbar performance predicted by the conventional and the improved methods with the measured one over a sandy terrain.

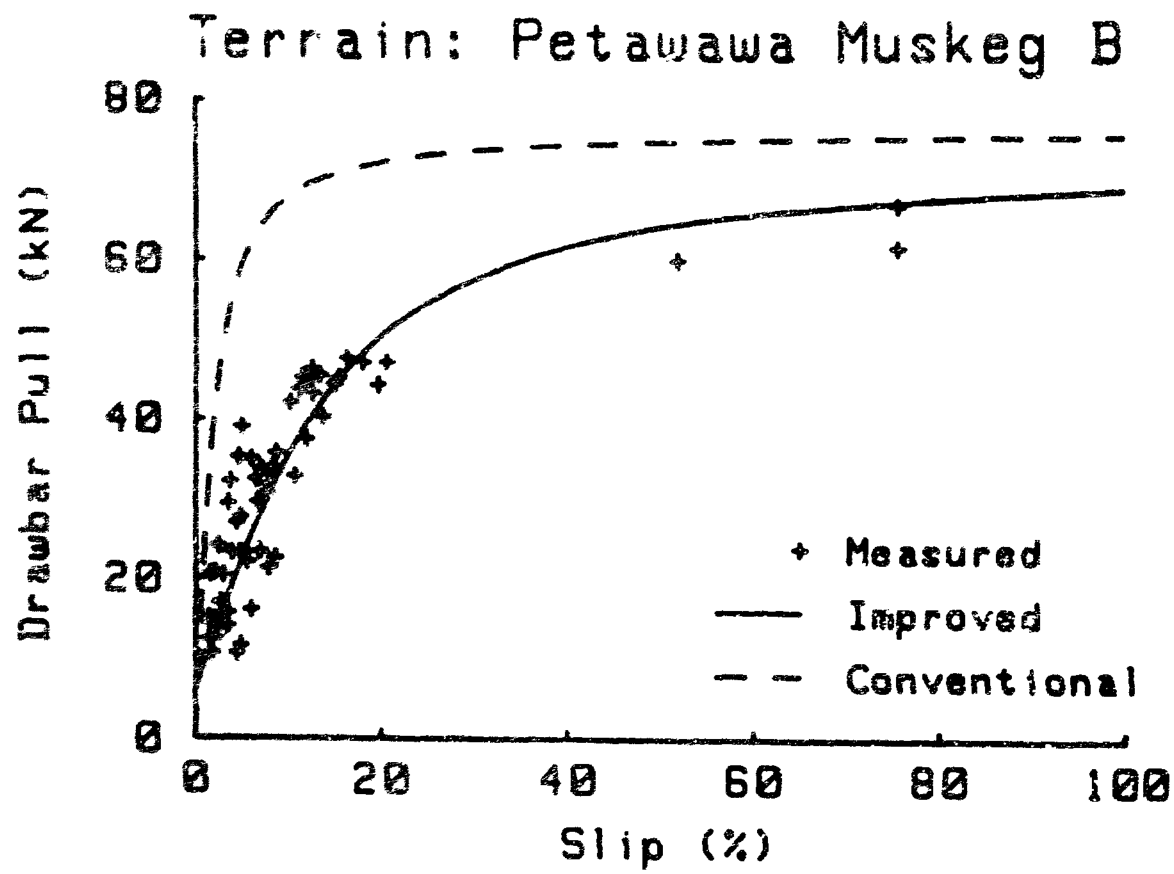

Fig. 11. Comparison of the drawbar performance predicted by the conventional and the improved methods with the measured one over a muskeg.